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A glacial origin for Sable Island: ice and sea-level fluctuations from seismic stratigraphy on Sable Island Bank, Scotian Shelf, offshore Nova Scotia

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Abstract: A database of interpreted geological cross-sections assembled from analogue high-resolution seismic-reflection profiles from Sable Island Bank has been compiled. A preliminary seismostratigraphy has enhanced understanding of the mid–late Pleistocene section. Numerous units and their bounding unconformities indicate a complex history of glaciogenic and sand-sheet deposition and associated sea-level fluctuations. A near-shelf-break ice-maximum position is interpreted for the Late Wisconsinan and inferred for earlier stades and/or glaciations. A late readvance sometime between 16 ka and 14 ka deposited a thick sand body over the transgressed bank, forming ancestral Sable Island. Modification and transport of sands accompanied a subsequent transgression. The database will provide the basis for compilation of a lithological and geotechnical zonation and a suite of maps depicting unit thickness and distribution, unconformities, and subsurface features, including geohazards, as well as large-scale (>1.5 m high) surficial bedforms.

Résumé : On a créé une base de données de profils géologiques interprétés obtenus à partir d'enregistrements sismiques analogiques haute résolution exécutés dans le banc de l'île de Sable. Un profil sismo-stratigraphique préliminaire nous a permis de mieux comprendre la coupe du Pléistocène moyen et supérieur. De nombreuses unités et les discordances limitrophes mettent en évidence l'histoire complexe des dépôts glaciogéniques et des nappes de sable, ainsi que des fluctuations du niveau de la mer qui leur sont associées. Selon notre interprétation, l'avancée maximale des glaces a atteint le rebord de la plate-forme continentale au Wisconsinien supérieur, position qui aurait également été atteinte lors des stades et/ou glaciations antérieures. Une réavancée tardive il y a entre 16 000 et 14 000 ans a déposé une nappe épaisse de sable sur le banc ennoyé, menant à la formation de la proto-île de Sable. La modification et le transport des sables ont accompagné une transgression ultérieure. La base de données servira de fondement pour la compilation d'une zonation lithologique et géotechnique et d'une série de cartes illustrant l'épaisseur et la répartition des unités, les discordances et les caractéristiques de la subsurface, y compris les risques géologiques, de même que la morphologie de fond à grande échelle (>1.5 m de hauteur).

INTRODUCTION

Seismic-reflection, borehole, and hydrocarbon well investigations have demonstrated that the upper tens to hundreds of metres of material on Sable Island Bank comprise Tertiary age, poorly consolidated sandstone and mudstone deposited in a regular, seaward-prograding pattern. These are overlain by a thick sequence of similar sediments (but with a greater reworked microfaunal component) of early Pleistocene age (King et al., 1974; Hardy, 1974; Boyd et al., 1988). Quaternary ice sheets left a record of multiple blanket deposits on the outer bank which thicken at the shelf break. On the mid- and inner bank a complex network of both deep and shallow, infilled channels cut into the older strata, in turn modified by a series of planar glacial and/or marine erosional-depositional processes. The latest of these includes a thick (30 m), sandy deposit referred to here as the Sable Island sand body upon which Sable Island sits. The Sable Island sand body comprises an elevated core of sediment with overlying progradational sand sheets and ridges. It thins significantly beyond and below the approximate 50 m water depth contour.

There remain large gaps in our knowledge of the geomorphic forms, features, and stratigraphy. The position of the glacial maximum and retreat margins has not been clearly delineated or time constrained; nor has the glacial and early postglacial sediment interaction with sea-level. A re-evaluation of a large, shallow seismic-reflection database collected by GSC Atlantic over the last 20 years is in progress. This includes a digital compilation, nearing completion, of geological cross-sections as interpreted from analogue (paper display) seismic profiles. The database includes over 8500 line kilometres of tracks (Fig. 1) These are high-resolution (< 0.3 m resolution) profiles (NSRF "V-fin" deep-towed sparker and Huntec™ DTS boomer) that generally characterize the upper 10–50 m below the seabed or medium-resolution air- water-, or sleeve-gun data. These studies aim to provide a regional mid- to late Pleistocene and Holocene geological framework for the outer Scotian Shelf. Ready accessibility and detailed information to potential users will be improved through CAD and GIS platforms, also allowing an improved ability to test, reinterpret, and update the database.

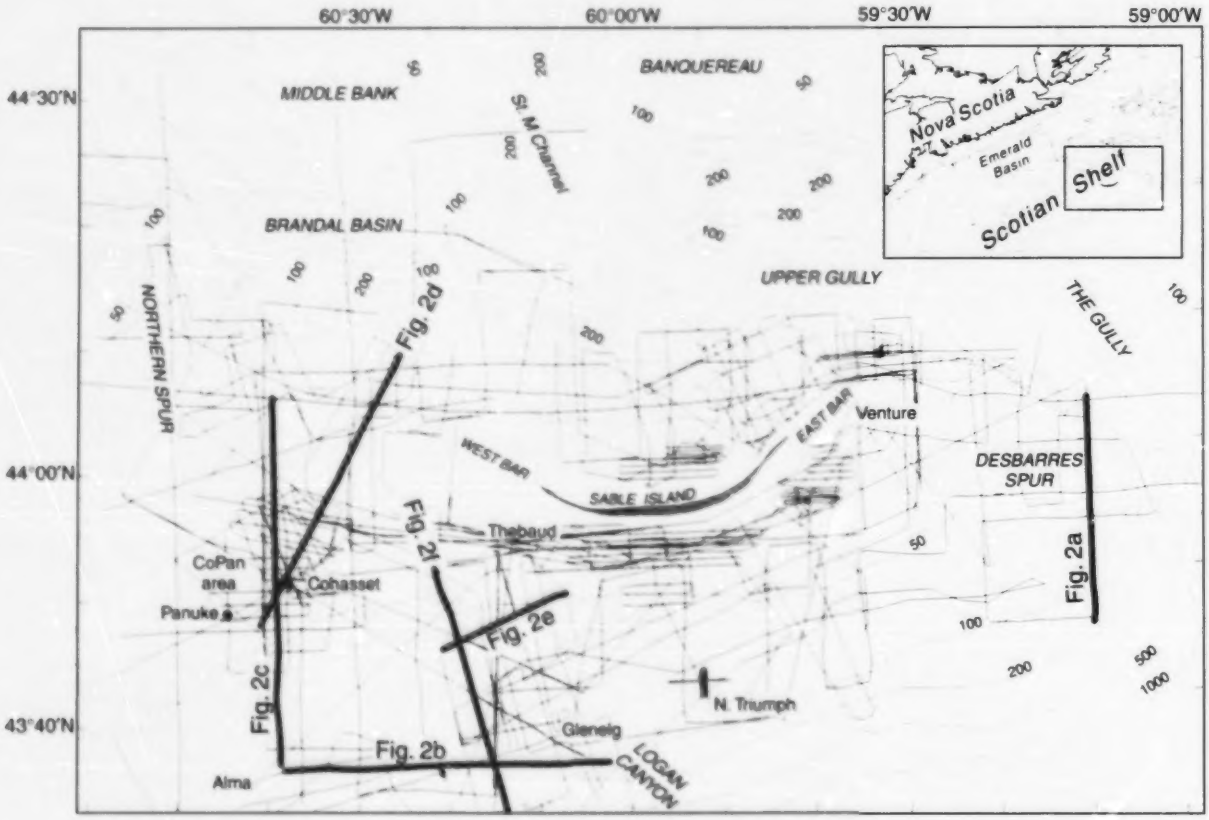

Figure 1. *Sable Island Bank region, with locations of geological profiles compiled from high-resolution seismic data and figure locations.*

The purpose of this paper is to outline database compilation techniques, indicate the nature of current geological studies and/or stratigraphic problems on Sable Island Bank, provide an outline of features and preliminary stratigraphic results from the compilation, and to show how this and further study impacts an understanding of ice-margin reconstruction, sea-level change, and paleosedimentary transport patterns. The potential such a framework has for engineering aspects related to offshore hydrocarbon development is also addressed through example.

COMPILATION OF THE GEOLOGICAL PROFILE DATABASE

Geographic coverage of the GSC Atlantic seismic-reflection database (Fig. 1) includes profiles with a variety of resolutions, depths of penetration, and quality and navigational accuracy. The large majority of profiles exist only in analogue (paper) format, with a large variety of scales and datum. Each relatively straight-line traverse was assigned a profile identifier (over 300 profiles) and a separate CAD drawing of geological profile was produced. The compilation procedure involves tracing, on paper, of all discernable coherent reflections and/or geological units and features, followed by scanning, vectorization, scaling, adjustment to a sea-level datum, and georeferencing according to the ship's track. The geological sections in this paper are typical products of this database. This procedure preserves, in detail, most of the geological information available on the seismic profiles in a readily accessible format. It also has the advantage of providing an assembly of data in a format which can be updated or reinterpreted at any later date or be used in unforeseen studies (e.g. it is already forming the basis for a bank-wide sedimentary bedform morphometrics database). The compilation enables a preliminary regional interpretation with correlation of units from profile to adjacent profile, provided here. The profiles also provide the 'raw' data for production of a suite of maps to illustrate the depth, form, and thickness of various units and their bounding surfaces and various attributes of surficial and buried features such as bedforms, channels, shallow gas, mass failures, etc. This should lead ultimately to a stratigraphic framework addressing the lithological and/or geotechnical nature, processes, and relative and/or absolute dating of the various stratigraphic elements.

GEOLOGICAL BACKGROUND

King (1970) first mapped the surficial geology of Sable Island Bank, differentiating a gravel lag and surficial sand body (Sable Island Sand and Gravel Formation) and recognizing a terrace at 115–120 m water depth attributed a low sea-level stand and coastal processes during the late Wisconsinan–Holocene transgression. Scott et al. (1987) recognized a relative sea-level rise since before 7 ka in the Sable Island area and discussed the dependency of sea-level history on ice-margin position and timing. They also presented geological profiles from high-resolution seismic sections, recognizing a flat horizon below the thick Sable Island sand body (since referred to as R-1), which they attributed to the transgression. The Sable Island sand body was ascribed to shallow-marine transport and reworking during transgression. The upper surface was further developed into a shoreface-connected sand-ridge field (Hoogendoorn and Dalrymple, 1986), its base marked by another regional horizon (since referred to as R-0). Boyd et al. (1988) recognized a buried-channel complex on the northern bank and interpreted a subglacial meltwater (tunnel valley) origin. Dodds and Fader (1986) recognized glaciogenic wedges interbedded with stratified sediment on the upper slope just west of Sable Island Bank and attributed them to ice advances. Mosher et al. (1989) demonstrated several ice-sheet advances here and dated the upper two wedges at ca. 70 ka and Late Wisconsinan (26–21 ka).

McLaren (1988) and Amos and Miller (1990) both developed stratigraphic frameworks and these remain the definitive works. The McLaren (1988) thesis identified many of the features and stratigraphic elements. The Amos and Miller (1990) work concentrated on the Cohasset-Panuke (CoPan) region and included paleoenvironmental (foraminiferal) and chronological analysis (^{14}C) of borehole samples. The two studies differed significantly in their interpretations of glacial and early postglacial history. McLaren suggested that the Sable Island sand body was deposited from a meltwater-dominated tidewater front and attributed prograding sands to proglacial delta processes. She associated the flat R-1 reflector below the Sable Island sand body to a preglacial event and attributed the overlying R-0 lag to the subsequent Pleistocene–Holocene transgression. Amos and Miller's (1990) chronology showed that the R-1 gravel lag and associated organic clay indeed represented the postglacial transgression. This appeared to be incompatible with an ice-margin origin for the Sable Island sand body and so the entire sand body was attributed to shallow-marine processes. King (1994) also adopted the moraine interpretation and attempted to seismically correlate a chronology from nearby Emerald Basin. A Younger Dryas (ca. 10.6 ka) age was suggested but later revised (King, 1996) to an older event of imprecise age. Stea et al. (1998) also concurred with the ice margin origin for the Sable Island sand body but invoked a glacio-isostatically induced regression to explain R-1. The present study attempts to reconcile some of the differences among previous workers, while maintaining their empirical observations.

SEISMOSTRATIGRAPHIC CLASSIFICATION AND DEPOSITIONAL INTERPRETATION

A tentative seismostratigraphic subdivision is presented in Table 1. Unit and bounding horizon designations are provisional, pending better bank-wide correlations and further subdivision. Numbering is from the top to base, rather than chronological order.

The conformable Tertiary–Quaternary boundary was identified at 220 m below sea level (b.s.l.) by Boyd et al. (1988) from a borehole on Sable Island. Profiles indicate at least a 0.5° seaward dip, which projected to the present shelf

Table 1. Provisional seismostratigraphy.

Fm	Setting	Member or Facies	Interpretation	Event and age comment
Sable Island Sand and Gravel Formation	Sable Island Sand Body (SISB) — Marine reworked sands	1(SR)	Reworked/remobilized sand ridges	Extreme storm events?
		U-1a	Reactivation horizons	
		2(SR)	Shoreface-connected sand ridges, eastward transport	Time transgressive with Holocene sea-level rise
		U-1b	Reorganization of current regime	
		3(SS)	Progradational sand sheets and coastal deposits	Since early postglacial; <14 ka?
		U-1	Renewed transgression and continued wavebase-generated lag ("R-0" of McLaren (1988))	
	Moraine and associated facies	4(TV)	Buried tunnel valleys on proximal side of moraine	
		U-2a	Subglacial meltwater channel erosion	
		4(CS)	Shallow and coastal sands ("Cross-bedded Sand" of Amos and Miller (1990))	
		4(MB) 4(DA)	4(MB) - core of morainal bank; in part subaerial 4(DA) - shallow marine ice distal apron; horiz. bedding	Late Late Wisconsinan glacial re-advance between 16 and 14 ka?
		U-2	Bank-top planation with transgression ("R-1" of Amos and Miller (1990) and McLaren (1988))	
Laurentian Formation	Marine/ glaciomarine	5(SM) 5(DM)	5(SM) - ridge/bar/channel sands on outer bank 5(DM) - deeper marine/glaciomarine equivalents	Synchronous with ice retreat?
	Partial or complete ice cover	5(GL) 5(PD)	Glaciogenic blanket (pro- and subglacial?)	Late Wisconsinan ice maximum; >18 ka?
		U-3	Erosion, marine and subglacial?	
	Ice cover	Undiff.	Undifferentiated multigenerational tunnel valleys along northern bank margin	Mid–Late Pleistocene
		U	Subglacial erosion, multiple stratigraphic depths	
	Periodic partial or complete ice cover and/or associated lowstands, poorly resolved	[redacted]	Glaciogenic blanket?	Mid–Late Pleistocene
		U-4	Erosional on bank-top	
		8(GL)	Glaciogenic blanket?	
		CH	Conformable horizon, possibly locally erosional	
		9(GL)	Glaciogenic blanket?	
		Undiff.	Unmapped or undifferentiated glaciogenic blanket(s)	
		U-5	Erosion, marine and subglacial?	
		[redacted]	Thick progradational blanket; glacial?	
		U-6	Subaerial channellization and shelf-break canyon equivalent to R-2 (Amos and Miller, 1990)	
		U-7	Equivalent to R-3 (Amos and Miller, 1990)	Early–Mid Pleistocene
		11		
		U-8	Largely unresolved, undulating horizon	
Banquereau		Plio.-Pleist.	Pliocene-Pleistocene boundary (Boyd et al., 1988)	Tertiary
		12(PG)	Seaward prograding; shelf construction	

across-shelf correlations unconfirmed

break indicates at least 500 m of Quaternary deposition. Only the upper approximately 100 m are resolved on the seismic data in this study. Within this wedge, eight regional unconformities (U-1 to U-8), and their bounding units display a variety of depositional character and types and degrees of erosion. Most are observed in the upper section (<70 m) where seismic resolution is highest. Horizons (depositional and erosional) are commonly beveled down in a northward direction through successive erosional events giving rise to a vertical confluence of unconformities. Thus some depositional age relationships are lost and seismic horizons can locally have a strong time transgressive nature. Boreholes along the mid-bank such as at the CoPan production area (Fig. 1) accordingly intersect truncated sequences and hiatuses.

The most complete late Quaternary geological section occurs on southeastern Sable Island Bank. Coincidentally, the seismic coverage is most sparse here and correlation of the deeper units and horizons along strike (to the west-southwest) is uncertain. An interpreted geological profile from southeast Sable Island Bank (Fig. 2A) shows the sequential nature of the outer shelf deposits. The stronger and more regionally continuous reflections display a slight seaward dip and an undulating geometry. Five major depositional sequences are depicted here (units 6(GL) to 10(GL)), bounded by undulating horizons. To the west, along strike, most of these units are more limited to a paleo-shelf-break position and major unconformable horizons are shallower. To the north, unit differentiation is lost through truncation by a complex of multigenerational, deep, infilled channels cut into undifferentiated lower Pleistocene strata. These are the eastward continuity of the tunnel valleys recognized by Boyd et al. (1988). McLaren (1988) mapped their approximate southern extent which follows an eastward path across the bank, located north of the island. There is no apparent connection with the canyons at the southern bank edge but ancestral canyons are recognized whose buried expressions extend 5–10 km on to the bank (e.g. Logan Canyon and canyons flanking the upper parts of The Gully). Various phases of prograding sand sheets in East Bar (unit 3(SS)) lie atop a depositional elevation over the undifferentiated tunnel valley complex (unit 4(MB)). This is the easternmost extension of the moraine identified by McLaren (1988). This flat-topped elevation thins southward where it assumes a weak conformable stratification (unit 4(DA), Fig. 2A, D).

Figure 2B, from the outer bank, shows a marked, relatively planar and seaward-dipping unconformity, U-6, marking the top of extensive channel cut-and-fill features. The channels are typically 5–20 m deep with rare occurrences up to 30 m and are generally less than 2 km across. They differ from the tunnel valleys in their smaller size and their distribution extending to the paleo-shelf-break. They may reflect subaerial drainage rather than subglacial. This is the equivalent of reflector R-2 of Amos and Miller (1990). Its erosional nature is now recognized to at least 120 m b.s.l. (150 m to base of channels). This lowstand has close connections with the ancestral Logan Canyon, a deep, infilled valley near the Glenelg development site.

Between unconformities U-6 and U-3 is a series of unconformity-bound blanket deposits (Fig. 2A, B). These were largely undifferentiated in previous studies and their genesis has received only ephemeral consideration, yet they represent most of the upper Quaternary section with a varied history of progradational, lowstand, and presumably glaciogenic processes. In general, the 'U' horizons are planar, slightly seaward dipping (<0.5°), and show some element of angular unconformity and an inflection point marking the paleo-shelf-break, presumably the position where erosion gives way to deposition. Unit 10(GL), bounded on top by unconformity U-5, displays crude progradation, occasional minor channellization, and has marked erosion at the paleo-shelf-break, continuing down to at least 125 m b.s.l. (Fig. 2B, C). The U-5 horizon itself is much more undulating than unconformity U-6. Unit 9(GL), above this, is relatively thick but seismically nondescript except for minor channelling and a progradational nature on the upper paleoslope. It commonly exhibits flat-lying internal horizons but with no recognized unconformable relationships. This is overlain by unit 8(GL) which is locally eroded on top (U-4) and overlain by unit 7(GL). This is, in turn, truncated by a very extensive, planar, and readily recognizable U-3 horizon.

Unit 6, overlying unconformity U-3, has a characteristically rough upper surface and, in the east, displays progradation and surficial channellization with stratified infill (unit 6(PG), Fig. 2A). Here, its base is marked by an infilling unit covering the underlying rough horizon, in the same manner as at the present seabed. This contrasts with its equivalents across most of the bank which display no coherent internal reflections, no discernable channels (unit 6(GL), Fig. 2E, F), and a smooth, planar base. Broad, trough-like basal erosion locally cuts through to underlying unit 7 (>10 m erosion). Its geometry and general lack of internal structure is in contrast to the overlying marine-influenced deposits of overlying unit 5. The homogeneous internal seismic character and broadly undulating upper surface is typical, though not diagnostic, of till. Near the outer-bank edge, locally elevated depocentres may represent morainic deposits (Fig. 2F). This, together with the regional, blanket-like distribution of unit 6, suggests a strong glacial influence. Deposition might be subglacial but a component of proximal ice-margin deposition is also likely. Ice cover to near the shelf break is inferred and its stratigraphic position indicates a Late Wisconsinian age. The easternmost bank unit equivalent (6(PG)) is a prograding proglacial apron which was subsequently, though temporarily, subaerially exposed and channellized. Topographic influence from The Gully could have acted to divert ice flow from here.

Similar, though less well defined elements (e.g. prograding, rough upper surface, erosional lower surface) are exhibited in the deeper section (units 7(GL) to 10(GL), Fig. 2A, B). Given the regular and repetitive nature, the assumption is made that the processes that formed them were similar. Hence, multiple glacial advances numbering at least five are inferred.

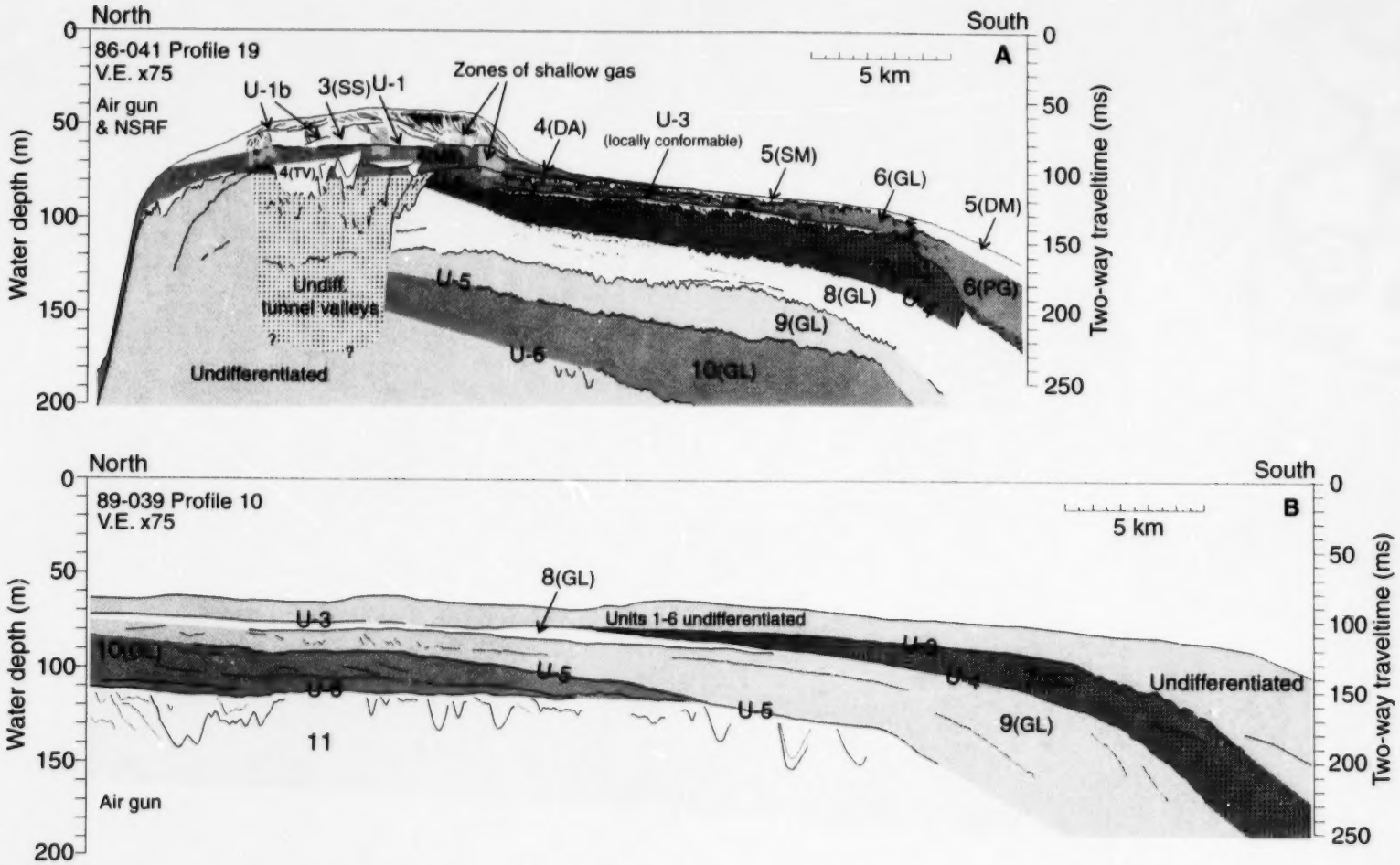

Figure 2. *Geological sections compiled from NSRF V-fin and air-gun seismic profiles (locations, Fig. 1) illustrating the stratigraphic units and their bounding surfaces.*

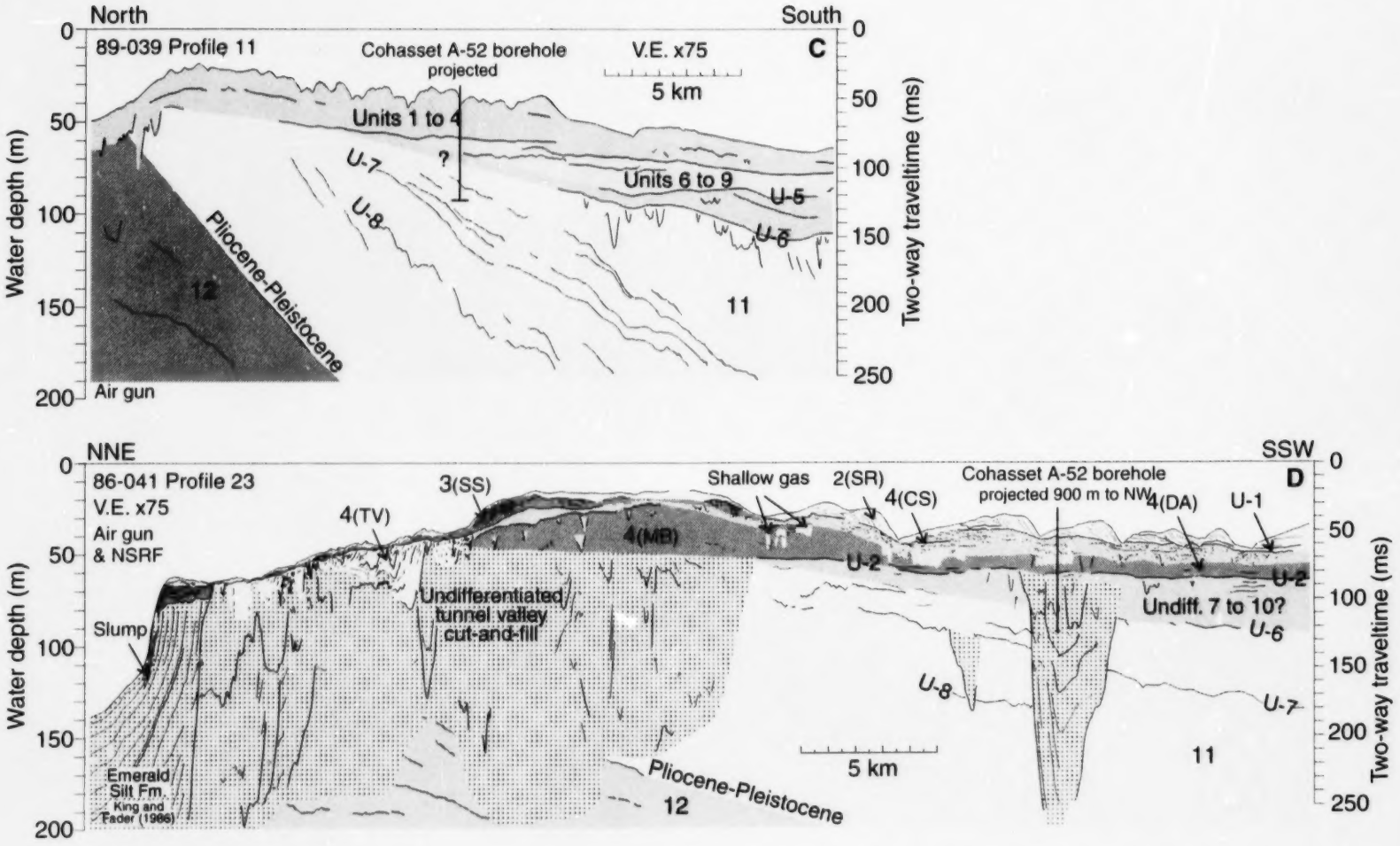

Figure 2 (cont.).

Overlying the glaciogenic blanket, unit 5(SM) displays clinoforms and crossbedding or small-scale cut-and-fill structures, attesting to a shallow-marine origin (Fig. 2E, F). Their shelf-break equivalents, 5(DM)), are thicker and display rare, weak, conformable reflections or indistinct, scattered, point-source, and discontinuous reflections. Its upper surface exhibits relief comparable in scale to iceberg scours (<5 m) though this origin is unconfirmed due to a thin, sandy cover. Underlying unit 6 is locally truncated on the outer margin (Fig. 2F) and this is attributed to undercutting associated with early sea-level rise, possibly coincident with ice retreat.

Figures 2E and F show that units 5 and 6 and locally older strata are truncated by the flat-lying U-2 horizon representing marine transgression, and the Sable Island sand body sits

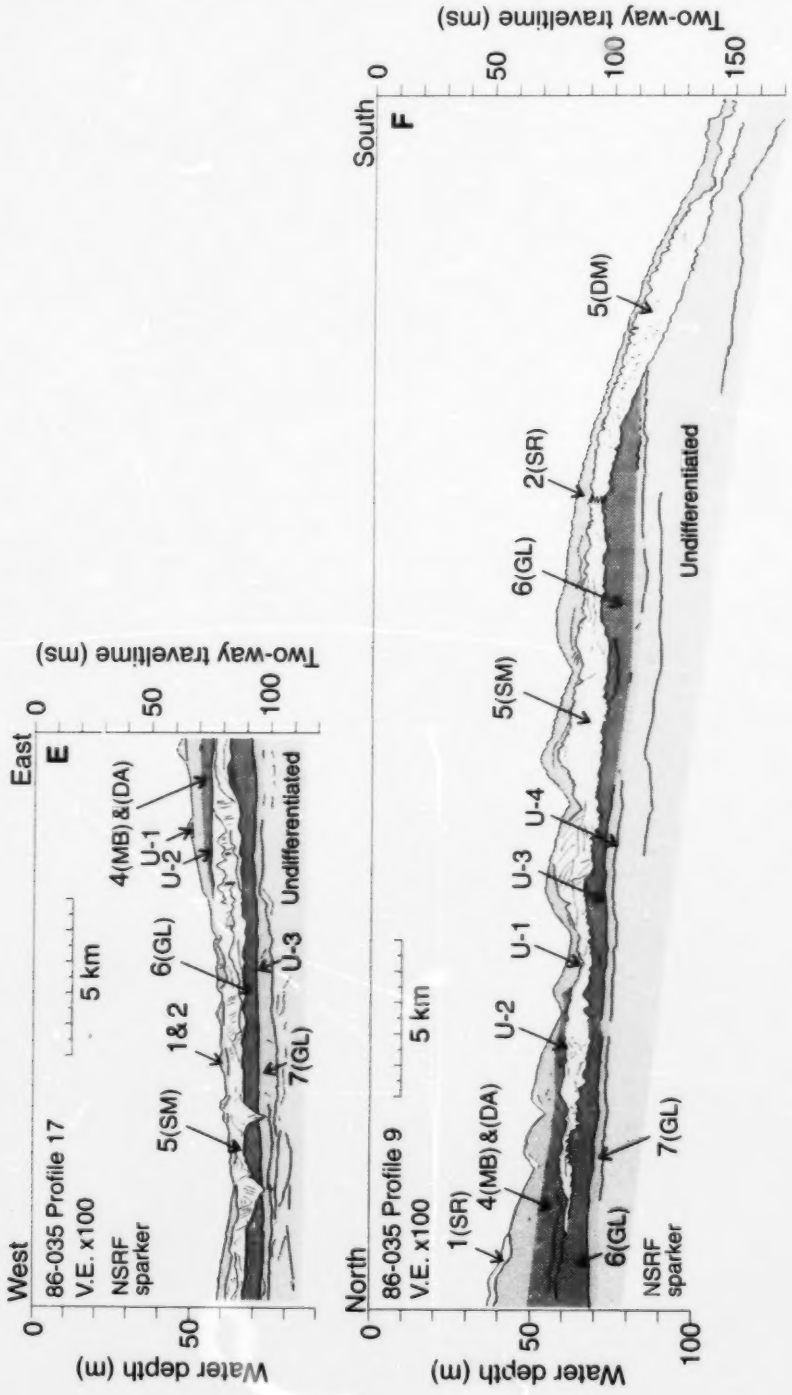

Figure 2 (cont.).

directly on this. Unresolved unit 6 remnants may be intersected at the Cohasset borehole (Fig. 2D). The Sable Island sand body itself comprises various seismic facies including a basal core, unit 6(MB) which is largely seismically featureless and/or homogeneous with the exception of its most seaward extent, 6(DA), which is a weakly stratified facies ("Conformably Bedded Sand" of Amos and Miller, 1990). Overlying this locally is unit 6(CS), characterized by strong but discontinuous reflections. On Northern Spur, East and West bars, and Desbarres Spur, numerous thick and extensive subunits with prograding and/or clinoform patterns (Fig. 2A, D) bounded by unconformities, represent separate phases of sand transport. More commonly, only one final phase of reactivation and sand transport is preserved as a thin blanket, or worked into various bedforms, overlying a variety of older deposits. The erosion surface is generally assigned a U-1 designation while recognizing its time-transgressive nature. Locally it cuts lagoonal sediments and peat beds from the Holocene transgression (Scott et al., 1988; C.L. Amos, T. Hume, G. Mastronuzzi, E. Centenaro, and F. Corbani, unpub. poster, 1998).

DISCUSSION

The varied history of progradation, sequential lowstands, and presumed glaciogenic processes in the section overlying the marked U-6 lowstand (Fig. 2B, C) marks a significant shift in depositional and erosional style with respect to the underlying Quaternary section. It may represent a change to intensified glacial influence on the bank. Projection of U-6 to the CoPan boreholes shows a correlation with R-2 of Amos and Miller (1990) which was assigned a 32–28 ka age. This young age seems problematic in light of the complexity of history following unconformity U-6, with at least five major depositional-erosional phases; it is doubtful that the following period (Late Wisconsinan) included so many deposition-erosion cycles. The seismic-borehole correlations are not straightforward near CoPan and are suspect. The units below U-2 are thin (<5 m), locally poorly constrained by their bounding reflections, and/or not intersected by the boreholes because of their channel-fill locations. This introduces the possibility of unrecognized sampling from younger deposits (including unit 6). Another variable is that the R-2 dates are from a study of adjacent Banquereau (Amos and Knoll, 1987) and there is no direct seismic correlation to Sable Island Bank.

A minimum age for the U-2 Late Wisconsinan transgression surface is provided by the directly overlying silty sand predating 10 ka with a shallow marine "cold" fauna of Amos and Miller (1990, their "conformably bedded sand"). This is the crudely stratified distal apron, 4(DA), equivalents of the seismically homogeneous Sable Island sand body ridge (Fig. 2A, D). The youngest date below the transgression surface is more than 16 ka. Tighter age constraint is difficult because of the hiatus. The U-1 surface, across the top of the Sable Island sand body (Fig. 2A, D), also resulted from transgression with associated deposition of lagoonal sediments and peat beds (McLaren, 1988; Scott et al., 1987, 1988; C.L. Amos, T. Hume, G. Mastronuzzi, E. Centenaro, and F. Corbani, unpub. poster, 1998). The sea-level curve of Scott et al. (1988) demonstrates a uniform rate of transgression with a maximum depth of about 50 m at ca. 11 ka, followed by a decreasing rate of sea-level rise to the present. As this curve incorporates events subsequent to initial Sable Island sand body deposition (above U-2), the author recognizes the connection between this and the erosion surfaces recognized within and across the Sable Island sand body at the base of shallow-marine sand sheets and ridges (Fig. 2A, horizons U-1b and U-1a), and the obviously time transgressive, regional U-1 horizon.

The two Late Wisconsinan–Holocene transgressions necessitate an intervening regression. Emergence of the Sable Island sand body by shallow-marine processes has been suggested (C.L. Amos, T. Hume, G. Mastronuzzi, E. Centenaro, and F. Corbani, unpub. poster, 1998). An alternative concept is a relative regression forced by the sudden flux of proglacial debris. The author invokes morainal bank deposition, forming the core of the Sable Island sand body and raising the deposit above sea level. This formed the ancestral Sable Island. Identification of the core of the Sable Island sand body as a terminal moraine by McLaren (1988) is based on heavy channellization on its northern side (including cutting the underlying U-2). She attributed this to subglacial meltwater because of their great depth and consequently inferred a terminal moraine for much of the Sable Island sand body. The same relationships are shown in numerous geological sections including new profiles across West Bar (M.Z. Li, E.L. King, and cruise participants, unpub. manuscript, 2000). The author confers with this morainic interpretation; however, rather than a Late Wisconsinan maximum position suggested by McLaren (1988), a younger glacial and/or sea-level scenario is suggested.

As shown below, the improved chronological constraints established since the McLaren (1988) study help substantiate the moraine interpretation by placing subglacial meltwater channels at this location after the Late Wisconsinan (U-2) transgression. The transgression surface indicates that relative sea level was already higher than 55 m below present sea level before Sable Island sand body deposition (Fig. 2D). The complex of channels (unit 4(TV)) cut to at least 75 m b.s.l. (locally 100 m) and thus attest to a process which was not subaerial. Tidal and/or storm scour of this magnitude is unlikely and would not be restricted to such a well defined southern limit. (There are none south of Sable Island.) Thus subglacial meltwater action is indicated.

The glacier terminus was likely nearly parallel to the Sable Island sand body, as envisioned by McLaren (1988). The maximum depth of channels generally decreases southward, probably reflecting the sloping glacier surface. The amount of ice terminus readvance to the south was at least several kilometres as truncation of U-2 attests, but the extent of the previous retreat is unknown. Accordingly, the role of glacio-isostatically induced shallowing (rebound) on U-2 is unknown and subsequent deepening (with advance) may have been significant but it was more than compensated for by proglacial deposition, which forced regression to at least 50 m below present sea level (curve of Scott et al. (1988)). Timing remains poorly constrained. The bank was ice-free

while U-2 formed after 16 ka and glacial ice persisted on Middle Bank until about 14.5 ka (till tongues of King and Fader (1986), dated in King (1996)).

At least five sequential till blankets with intervening stratified glaciomarine sediment are recognized on newly collected seismic profiles in Brandal Basin, north of Sable Island Bank (M.Z. Li, E.L. King, and cruise participants, unpub. manuscript, 2000). These are thought to be near correlatives with the Emerald Basin till tongues and one of the uppermost is a possible correlative with the Sable Island sand body moraine. Sites for potential coring and/or dating are identified (M.Z. Li, E.L. King, and cruise participants, unpub. manuscript, 2000).

The distal moraine apron (unit 6(DA)) was marine and relatively quiescent (possible sea-ice cover), but eventually there would have been a dynamic coastline above this, along the southern moraine flank. This apparently reworked the moraine depositing unit 6(CS), "cross-bedded sands" of Amos and Miller (1990). Subsequent transgression to form U-1 across much of the moraine-top would have initiated soon after glacier retreat. Coastal processes locally maintained the (shrinking) Sable Island. Erosion on the U-1 horizon was most vigorous at the distalmost Sable Island sand body (about 60 m b.s.l., Fig. 2F) where a local nick-point and partially preserved bars and sand sheets developed, and occasional (?tidal) channelling cut down to the U-2 level. This likely reflects the changed hydraulic regime on the bank imposed by the new coastal barrier but it might also reflect a relative sea-level stillstand as early postmoraine glacio-isostatic rebound matched eustatic rise.

GEOHAZARDS AND ENGINEERING-RELATED FEATURES

The geological profiles include information on presence and/or extent of buried channels, the nature of their infill, and the location and depth of shallow gas. Also, a surficial bedform morphometrics database will document characteristics such as water depth, height, wavelength, and symmetry of bedforms (>1–2 m height). The detail, accessibility, and geographic coverage provided presents a context for local, applied investigations such as site, foundation, and pipeline and cable surveys.

These are sand-dominated deposits, largely reflecting their midshelf fine-grained semilithified Mesozoic–Cenozoic source material and a prevalence of marine and glacial meltwater reworking processes. Thus, even if the glaciogenic units were entirely subglacially deposited they are not likely typical of clay- and cobble-rich (diamicton) tills on land and the inner shelf. Nevertheless, it can be inferred that local, interbedded clays and scattered or layered boulders and/or cobbles are likely in the near subsurface on the outer bank and below the relatively homogeneous, thick (tens of metres) sands of the Sable Island sand body on the midbank and northern bank. Here, ubiquitous channel fill would be highly and locally variable in clay content and compaction degree.

The large variation in distribution, thickness, genesis, and history of transport or compaction (glacial overriding or exhumation-related) of the various units has been demonstrated. These factors can have significant affects on foundation properties. Even along the outer bank conditions are variable; thickness of units 7–9, for example, vary by a factor of two between Glenelg and Alma, despite only a few metres difference in water depth.

Shallow gas is widely distributed but generally of local extent, manifest as enhanced coherent and point-source reflections and masking. Masking is nearly ubiquitous in the basinal areas immediately north of the bank. Otherwise, a general association with gas occurrence and deep channels and possibly with shallower lagoonal deposits is apparent.

CONCLUSIONS AND SYNTHESIS OF SABLE ISLAND BANK HISTORY

Compilation of a digital database of geological profiles from high-resolution seismic-reflection data is nearing completion and will provide ready access to geological conditions and features, including geohazards. An improved stratigraphic framework is evolving from the database and a preliminary synthesis follows.

Tertiary and Early Pleistocene shelf progradation gave way to a series of marked unconformities representing lowstands assumed to reflect glacio-isostatic and eustatic conditions. Following a major lowstand, likely to 150 m below present (U-6), a series of glaciogenic sheets were deposited, numbering at least five, and presently interpreted as representing multiple glacial ice extensions at least partially across the bank and locally to the shelf break. The Late Wisconsinan ice maximum position (not dated directly) locally extended to the shelf break, modifying the bank through planar erosion (U-3). It deposited unit 6 across most of the midbank to outer bank as both a proglacial, prograding blanket with a channellized and/or iceberg-scoured top and a hummocky proximal or subglacial blanket. Ice retreat was followed by or coincident with shallow-marine reworking and transport of sands into bars, ridges, and channels whose dissected remains constitute unit 5(SM) and its deeper water equivalents 5(DM). Ice retreat from the bank resulted in exposure to full marine and coastal forces on the shallowest parts, planing it nearly flat (U-2). Southward readvance of the glacier margin, probably through the channel between Middle Bank and Banquereau, informally known as St. M channel (Fig. 1), and spread across the northern bank, depositing the Sable Island sand body core (unit 4(MB)) and forming ancestral Sable Island. This was a tidewater and subaerial morainal bank, sourced largely through tunnel valleys. The timing is poorly constrained by the initial transgression after 16 ka and the last vestiges of midcontinental shelf glacial ice by 14.5 ka. This readvance forced a marine regression while depositing, the core, a distal marine apron (4(DA)), and local coastally reworked sands (4(CS)). With final ice retreat, transgression was renewed (U-1), modifying much of the moraine, first with a northerly transport of sediment and then a redistribution

into the bars, sand ridges, and thick sand sheets. Sable Island was maintained but grew much smaller with continued sea-level rise.

An improved understanding of the geological history also contributes to better characterization of deposits for engineering purposes and this should prove useful with future incorporation of lithochronological and geotechnical information into the framework.

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